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Original Article

EXPERIMENTAL INVESTIGATION OF CO-GASIFICATION OF COAL AND BIOMASS WITH CO_2 CAPTURE USING CaO SORBENT

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ABSTRACT

Gasification is a promising eco-friendly technology to meet the current and future energy demands. One of the main issues of gasification is the presence of major greenhouse gas CO_2 in the product gas. The aim of this paper is to study the effect of parameters on sorbent-enabled gasification process to reduce CO_2 emissions. Experimental investigation of the effect of parameters Equivalence Ratio(ER), Steam to Fuel Ratio (SFR), a Sorbent-to-Fuel Ratio (SOFR) and a Coal-to-Biomass Ratio (CBR) on syngas composition in the co-gasification of coal and biomass is performed in a lab-scale biomass gasifier. Results indicated that the addition of sorbent during gasification decreases the CO_2 content and increases H_2 yield. An increase of 21.5% in H_2 and reduction of 24.3% in CO_2 emissions is achieved at CBR of 0.25/0.75.

***KEYWORDS**: Biomass Gasification, Co-Gasification, Equivalence Ratio (ER), A Steam-to-Fuel Ratio (SFR), A Sorbent-to-Fuel Ratio (SOFR) & Coal-Biomass Ratio*

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INTRODUCTION

There is a growing concern over increasing environmental issues such as global warming, depletion of fossil fuels due to increasing energy demands. While coal and biomass are abundant in India, an eco-friendly technology is necessary to utilize these resources effectively with minimum environmental impact and maximum efficiency. Gasification had been the focal point of many researchers across the world for the past two decades. One of the disadvantages of gasification is the presence of major greenhouse gas CO_2 in the product gas. Several methods have been proposed by researchers to increase H_2 production, and reduce the CO_2 content. Majority of the works have been on modeling the process with different gasifiers, biomass feed stocks, and sorbent materials. Nicholas et al [1] reported one of the initial works on enhanced H_2 production using CaO sorbents in

steam gasification of biomass. They conducted kinetic modeling the process and reported that the key variables are reaction temperature, pressure, steam-to-biomass ratio, and sorbent loading. The study focused mainly on the durability of the sorbent and its effectiveness. According to them, there is an increase of about 40% H_2 when sorbent is used. Ligang Wie et al [2] conducted the experimental study in a laboratory scale External Circulating Concurrent Moving Bed (ECCMB) for production of H_2 from biomass. They reported that SBR and sorbent-to-biomass ratio are critical parameters for increasing the H_2 yield. Parthasarathy et al [3] conducted a comprehensive review of the production method and effect of process parameters for H_2 production. They reported that the Steam Methane Reforming (SMR) method has the highest efficiency, followed by auto thermal reforming and coal/biomass gasification. They concluded that biomass type (composition), feed particle size and catalyst also are important factors to be considered in addition to SBR and SOBR. Shakirudeen et al [4] studied the cyclic stability, regenerability and high-temperature adsorption of CO_2 of CaO based sorbents. They reported that CaO absorbs CO_2 up to 700°C and then desorbs above that by calcination. Amal S et al [5] used tire char as the catalyst for tar removal in a two-stage fixed bed reactor and increased H_2 yield. Volatiles released from feedstock at 500°C in the first stage are sent to the second stage for biomass steam gasification. They found that even though tar decomposition is significant due to catalytic activity the release of minerals resulted in the decreased H_2 production. They reported that when the steam temperature is raised, H_2 increased due to increased reaction rates. Bo Zhang et al [6] studied the effect of dolomite, limestone and their combinations on hydrogen production. Gasification and sorption reforming was carried out in two different beds maintained at 900°C and 730°C using additives in both beds. They observed that dolomite resulted in higher H_2 than with CaO and MgO. In all the cases, Ni impregnation increased the yield but decreased the sorption capacity. Richard Bates et al [7] investigated the biomass gasification in a Fluidized Bed Reactor (FBR) using multi-scale models and experimentation. They used a bench scale externally heated FBR and performed air-steam gasification. They found that bed additives and mixing pattern plays a vital role in the tar formation and syngas composition. Tar formation significantly increased with increase in oxygen. They reported that at an ER of 0.2 and SBR of 0.6 the gasifier reached autothermal state and maximum Cold Gas Efficiency (CGE) is achieved at ER of 0.15. Bin Li et al [8] studied the effect of Ca-based adsorbents and Ni-based catalysts on corn stalk gasification in two-stage fixed bed reactor. They used calcined $CaCO_3$, Olivine, and Dolomite to prepare the adsorbent and a bifunctional NiO/CaO catalyst/adsorbent. The results indicated that addition of calcined sorbents significantly improved H_2 concentration by absorbing CO_2. They found that magnesium species increased the catalytic effect and a highest H_2 concentration of 85.1 vol% was achieved with minimal CO_2. Yhaui Xiao et al [9] proposed a novel Decoupled Dual Loop Gasification system (DDLG) by separating pyrolysis/gasification, tar cracking and char combustion reactions into 3 reactors. Fuel/combustor loop and combustor/tar cracking loops were created separately and the processes were individually optimized. Pine sawdust is used as feed-stock and calcined Olivine is used as adsorbent as well as the catalyst for tar cracker. They found that an increase in temperature increased pyrolysis activity and tar cracking. They achieved an H_2 concentration of 40.8% and minimal tar content of 14.1 g/Nm^3 at an SBR of 1.2 and temperature of 850°C. Fangzhu Jin et al [10] studied the effect of Ca addition on H_2 yield and catalyst performance in biomass gasification. They found that an increase in the addition of Ca decreases the effectiveness of the catalyst. Haiping Yang [11] investigated the effect of potassium salt loading on CaO during gasification of biomass. They found that the addition of potassium impregnated CaO significantly increased CO_2 adsorption and cyclic performance.

It can be observed from the above discussion that most of the previous works are focused on studying the effect of different absorbents and catalysts for improved performance and durability in biomass gasification. Also, most of the

studies are model-based and not experimental works. Very few works are reported on the addition of these adsorbents in coal and co-gasification of coal/biomass. The present study is therefore aimed at studying the effect of sorbent addition in air-steam gasification of woody biomass and high ash Indian coal. In this study, experimental investigation is performed on lab-scale downdraft gasifier using woody biomass and Jharia coal. CaO is used as adsorbent and effect of parameters Equivalence Ratio (ER), the steam-to-fuel ratio (SFR), a sorbent-to-fuel ratio (SOFR) and a coal-to-biomass ratio (CBR) on syngas composition are investigated. Major reactions are shown in table 1. Stoichiometric air quantity and ER are calculated using equations (1) and (2).

Table 1: Major Reactions Taking Place during Gasification

Process	Reaction
Oxidation	$C + 0.5O_2 \rightarrow CO\ , \Delta H^{\circ} = -268\ kJ/mol$ $C + O_2 \rightarrow CO_2, H^{\circ} = -\ 406\ kJ/mol$ $H_2 + 0.5O_2 \rightarrow H_2O, \Delta H^{\circ} = -258.8\ kJ/mol$
Water Gas Shift Reaction	$C + H_2O \rightarrow CO + H_2, \Delta H^{\circ} = +131\ kJ/mol$
Boudouard Reaction	$C + CO_2 \rightarrow 2CO\ , \Delta H^{\circ} = +172\ kJ/mol$
Shift Reaction	$CO + H_2O \leftrightarrow CO_2 + H_2, \Delta H^{\circ} = -42\ kJ/mol$
Methanation	$C + 2H_2 \rightarrow CH_4, \Delta H^{\circ} = -75\ kJ/mol$

$$Stoichiometric = 4.23 * [2.67C + (8H - O) + S] \quad (1)$$

Where C, H, O, and S are wt. % of Carbon, Hydrogen, Oxygen, and Sulfur taken from the Ultimate analysis.

$$Equivalence\ Ratio\ (ER) = \frac{\left({}^{Air}/_{Fuel}\right)_{Actual}}{\left({}^{Air}/_{Fuel}\right)_{Stoichiometric}} \quad (2)$$

EXPERIMENTAL SETUP

Figure 1 shows a line diagram of experimental setup. It consists of throatless downdraft gasifier called reactor, cyclone separator, tar scrubber, air blower, and steam generator. A hopper is fixed at the top of the reactor to supply the feedstock. The reactor assembly is water sealed at the top and the bottom (below the grate) to avoid escaping of the gases. The inner side of the reactor consists of firebrick lining to protect the reactor walls to avoid heat transfer to the surroundings. The reactor consists of air supply holes (tuyers) near the combustion zone. The gas produced in the reactor passes through the cyclone separator where the particulate matter like ash, dust, etc., are separated and collected in a chamber provided at the bottom. The dust-free gas is then passed through the water scrubber in which the tar is separated and collected in the bottom tank filled with water. The air blower is provided to supply the air and the flow is measured using rotameter. A steam generator is used to produce and supply the steam. Four thermocouples are fixed to the reactor to read the temperatures at four main reaction zones viz., drying, pyrolysis, oxidation (combustion) and reduction (shift reaction).

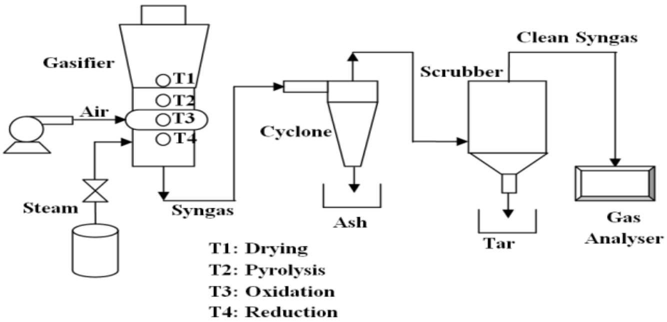

Figure 1: Block Diagram of Experimental Setup

Figure 2: Laboratory Experimental Setup

EXPERIMENTAL METHODOLOGY

Experimental investigation of the effect of ER, SFR, SOFR, and CBR on the syngas composition is performed with and without using adsorbent. Woody biomass and bituminous (Jharia) coal are used as feed stocks while CaO is used as an adsorbent. The feedstock is prepared in the form of pieces with size ranging from 10-25mm in the thickest part. The elemental analysis of coal and biomass are obtained from CHNS and Oxygen analysis while moisture content is obtained from the thermogravimetric analysis. Table 2 shows the elemental analysis of biomass and coal. A specified amount of feedstock is filled in the reactor-hopper and the feedstock consumption rate is calculated by measuring the amount of feedstock remaining after the gasification process is complete. The air and steam are supplied at atmospheric pressure and flow rates are controlled and measured using flow meters. Four thermocouples (T1-T4) are used to record the temperature of four zones of the reactor viz., drying, pyrolysis, oxidation, and reduction. At the outlet the dust and tar free gas are collected in the gas sampling bags and analyzed using gas chromatography. For co-gasification is prepared by mixing coal and biomass in specific proportions of 0.25/0.75, 0.5/0.5 and 0.75/0.25. Feedstock-adsorbent mixture is prepared by mixing the feedstock with anhydrous CaO (dried and powdered) in different ratios.

Table 2: Proximate and Ultimate Analysis of Feedstocks

Fuel	Proximate Analysis				Ultimate Analysis					
Component	**M**	**FC**	**VM**	**ASH**	**C**	**H**	**N**	**Cl**	**S**	**O**
Jharia Coal	6.94	36.4	28.5	28.2	49.3	4.81	1.11	0.08	0.31	9.25
Biomass	4.73	68.72	25.01	1.48	48.27	6.82	0.71	0	0.33	37.65

RESULTS AND DISCUSSIONS

Figures 3(a-d) shows the effect of operating conditions ER and SFR on biomass gasification in both with and without using CaO sorbent. Addition of sorbent clearly indicates the increase in H_2 content and decrease in CO, CO_2 contents. It is observed that H_2 content is increased by 21.5% and CO_2 content is decreased by 24.3% due to addition sorbent. Figure 3(e) shows the effect of sorbent to biomass ratio on syngas composition. It can be seen that an amount of sorbent increases H_2 increases till SOFR of 0.8 and then decreases. This phenomenon is attributed to the decreased reactivity of biochar due to the masking effect. CO and CO_2 continue to decrease with the addition of sorbent but with diminishing effect of sorbent addition.

Figures 4(a-d) depicts the effect of operating conditions and on coal gasification with and without using CaO sorbent. A similar trend is observed in a change in the amount of H_2 and CO_2 formation. However, the difference is less when compared to that of biomass which can be attributed to higher reactivity of biomass resulting from its sparse pour structure. The effect of sorbent addition is shown in figure 4(e). It can be observed that H_2 increases initially with an increase in sorbent and then decreases, while CO and CO_2 decrease continuously. The maximum H_2 is obtained between SOFR of 0.8 to 1.2. Figure 5 shows the effect of the C/B ratio on gas composition. It is observed that the maximum H_2 of 54.62% is obtained at a CBR of 0.25/0.75, while minimum CO_2 of 7.37% by volume is observed at CBR of 0.75/0.25.

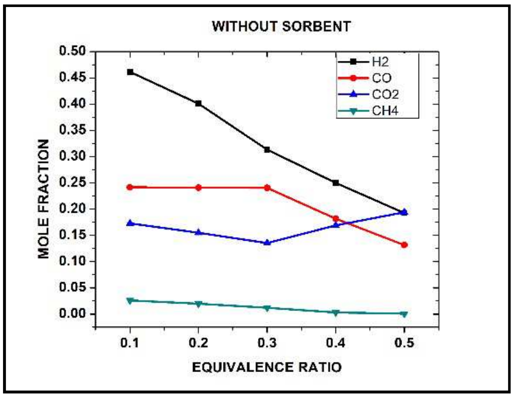

Figure 3(a): Effect of ER Without CaO

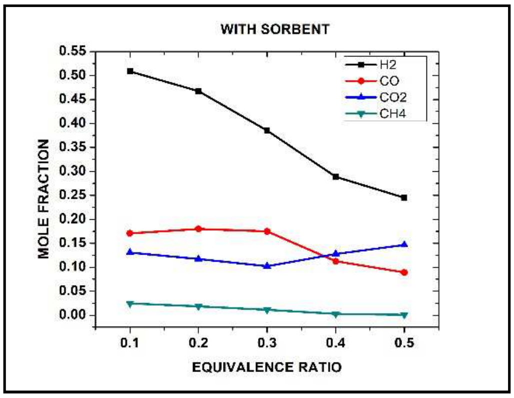

Figure 3(b): Effect of ER With CaO

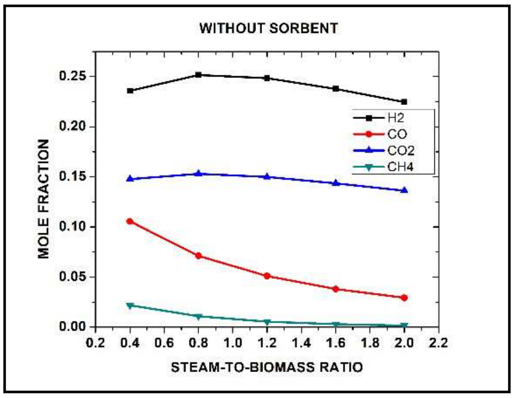

Figure 3(c): Effect of SFR Without CaO

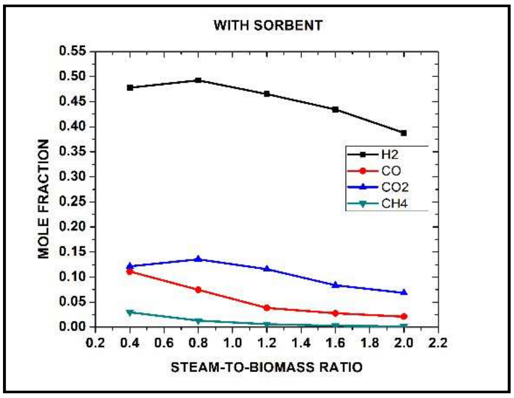

Figure 3(d): Effect of SFR With CaO

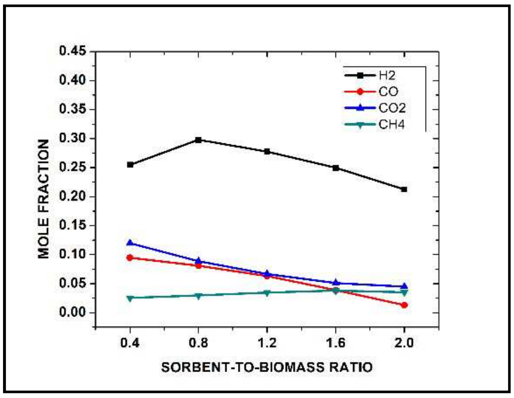

Figure 3(e): Effect of SOFR

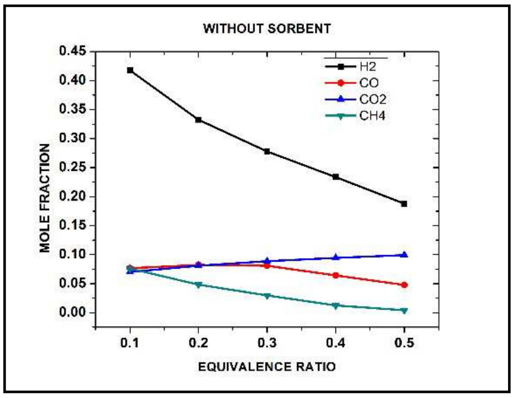

Figure 4(a): Effect of ER Without CaO

CONCLUSIONS

Experimental investigation of co-gasification of an Indian coal and woody biomass is performed in a throat less downdraft gasifier. The effect of operating conditions ER, SFR, SOFR, and CBR are investigated both in the presence and absence of CaO sorbent. The results indicated that there is a definite increase in the H_2 reduction in CO_2 quantities while using sorbent. The maximum increase of 21.5% is achieved in H_2 quantity, while CO_2 emissions are decreased by 24.3% when sorbent is used. The effectiveness of sorbent decreased beyond a SOFR of 0.8 due to the masking effect of $CaCO_3$ on the reactants. In the co-gasification highest amount of H_2 is obtained at CBR of 0.25/0.75.

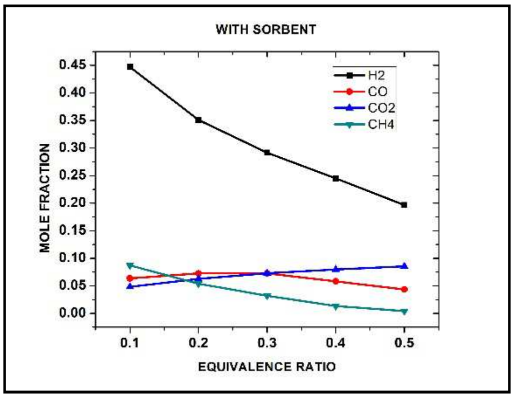

Figure 4(b): Effect of ER With CaO

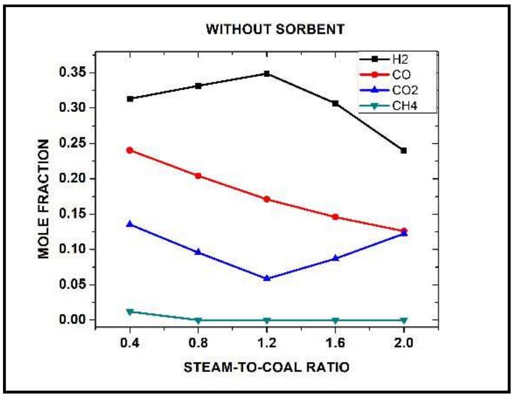

Figure 4(c): Effect of SFR Without CaO

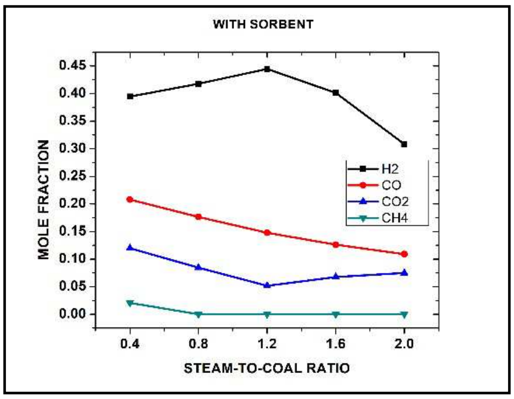

Figure 4(d): Effect of SFR With CaO

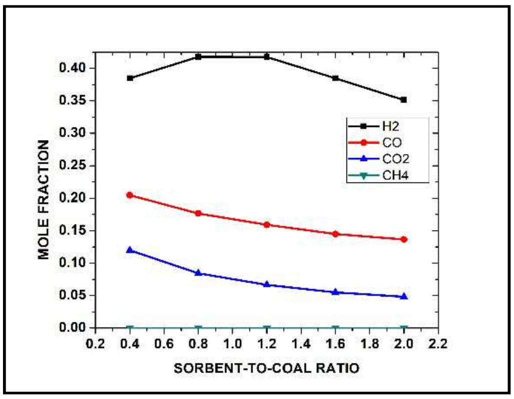

Figure 4(e): Effect of SOFR Without CaO

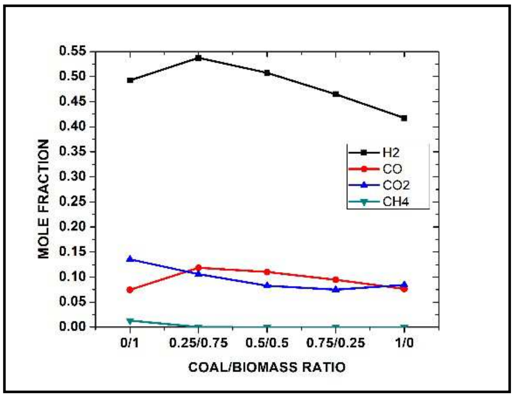

Figure 5: Coal/Biomass Ratio

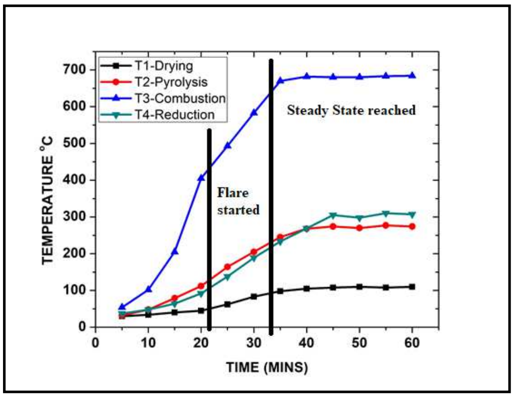

Figure 6: Temperature Profile

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